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Rapid Operational Access and Maneuver Support (ROAMS) Platform for Improved Military Logistics Lines of Communication and Operational Vessel Routing

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PURPOSE: The purpose of this Coastal and Hydraulics Engineering Technical Note (CHETN) is to document and demonstrate the Rapid Operational Access and Maneuver Support (ROAMS) v2.0 computational scripting/application program interface (API) platform. ROAMS provides improved knowledge of potential lines of communication and vessel routes through hydrodynamic modeling and path optimization under a variety of environmental conditions and input-information qualities/sources. Primary focus of this document is given to the implementation of penalty barrier-based path optimization to provide guidance for subsequent work. The platform additionally provides object-oriented, script-based interaction with principal U.S. Army Corps of Engineers (USACE) hydrodynamic models.

BACKGROUND: Military undertakings in waterborne environments can be broadly classified into two types of activities: logistics and operational. Logistics activities are concerned with the establishment of lines of communication (LOC) to efficiently move equipment, personnel, and provisions from an offshore intermediate staging base (ISB) to a Sea Port of Debarkation (SPOD). The SPOD may be but is not limited to a world-class port, an unimproved beach at the coastline, or an upstream site in an estuary. Locations are typically chosen through a combination of expert judgment, analyses of nautical charts, and scenario planning to avoid known environmental austere obstacles such as shoals, reefs, and wreckage. The qualitative nature of the military logistics planning process causes direct comparison of LOC to be challenging; furthermore, qualitative methods do not guarantee the selection of an optimal site that maximizes total throughput and up-time percentage. The military has some logistics tools that facilitate planning of this type such as the Analysis of Mobility Platform (AMP) (Mckinzie and Barnes 2004). Other systems to conduct environmental measurements, such as Joint-Logistics-Over-The-Shore (JLOTS) Environmental Monitoring System (JEMS), typically lack the capability to translate those measurements into applicable decisions (U.S. Transportation Command 2016).

Military operational activities constitute any other type of actions that do not principally involve military logistics (Defense Technical Information Center 2011). These activities often require routes to be revised during the operation as environmental and mission conditions evolve. Operational activities are more likely to encounter obstacles including enemy combatants, manmade impediments such as mines, scuttled vessels, or environmental obstructions like reefs and shoals. An initial route for such operations is selected much like the military logistics case. Subsequent adjustments to routes may be done on an ad hoc basis at the discretion of the commanding officer using the improved information about the mission state.

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The U.S. Army Engineer Research and Development Center (ERDC), Coastal and Hydraulics Laboratory (CHL), is developing the capability for military planners to rapidly optimize vessel LOC/routes by extending capabilities of the ROAMS modeling platform. The ROAMS platform is a model-based, decision support tool aimed at facilitating strategic logistics and operational planning in anti-access area-denial (A2AD) environments (Farthing et al. 2014). The platform allows users to rapidly generate models of a water environment in limited information conditions, utilizing the Adaptive Hydraulics (AdH) and Steady-state spectral wave (STWAVE) computational engines for the base two-dimensional (2D) hydrodynamics and waves, respectively. The intent of ROAMS is to provide analysis of entry LOC/routes to optimize and determine the effectiveness of each in changing conditions such as enemy activity, weather, bathymetry, terrain, and sea state. This work discusses the capabilities of ROAMS, in particular the *routing* toolbox, and presents a case study in a northeastern American metropolitan area.

METHODOLOGY: The ROAMS platform provides expanded analysis, model automation, and enhanced visualization tools to aid in logistical planning or waterborne movement of troops, equipment, and supplies under varying conditions. The majority of development within ROAMS v2.0 is focused on increasing command line capabilities to provide an API for data retrieval. ROAMS v2.0 is comprised of four main toolboxes—*AdH,* which models hydrodynamics; *STWAVE,* which models the wave environment; *domain,* which manages data acquisition and manipulation; and *routing,* which determines vessel paths through the environment—that are implemented as independent Python packages to support distinct portions of the analysis. The independent toolbox structure allows utilization of only the minimal subset of the ROAMS code base necessary to complete a task, facilitating computational performance and code quality. The *AdH* and *STWAVE* toolboxes serve as object-oriented, Pythonic wrappers for the similarly named modeling engines used by USACE.

The following sections discuss the capabilities of each of the four main ROAMS toolboxes. A fifth ROAMS toolbox, *util*, contains supporting functionality such as meshing, projection, and unit conversion. It is also a part of ROAMS v2.0 but will not be discussed in detail.

Toolbox: AdH. AdH is a finite element engine capable of solving the 2D and three-dimensional (3D) shallow water equations, the 3D Navier-Stokes equations, and the 3D groundwater equations. Source code for the AdH engine is actively developed and manipulated by the ERDC CHL[1].

The purpose of the AdH toolbox is to estimate water depth and velocity to better determine vessel spatial and temporal accessibility within a simulated region. The AdH toolbox additionally provides a means by which to create, run, and post-process an AdH model. Generated AdH simulations can be coupled to STWAVE model instances to account for wave setup effects. Use of the AdH toolbox is not required to establish water depths for routing analyses as known bathymetry may be used in its place, but the model remains an option when an alternative source of hydrodynamic information is unavailable and sufficient environmental data exist to establish boundary conditions. The toolbox functionality is accessed by means of an AdH model object that contains all of the parameters specific to a single AdH model. These parameters include all of the associated input cards, domain meshes, initial conditions, boundary conditions, and results. All

[1] *The Adaptive Hydraulics (AdH) Modeling System*. U.S. Army Engineer Research and Development Center, Coastal and Hydraulics Laboratory, Vicksburg, MS.

functionality of the AdH engine is accessed through setting the object parameters or calls to the AdH model object functions.

Toolbox: STWAVE. STWAVE is a finite difference engine for solving the steady state wave actions balance equation to determine wave height, period, direction, and spectral shape between the offshore and nearshore in less than 40 meters (m) of water. The capabilities of the STWAVE engine include solving for wave refraction, shoaling, current induced effects, and wind/wave growth (Smith 2016)[1].

The STWAVE toolbox estimates the wave height and period to anticipate when and where the water surface becomes too energetic to operate. The STWAVE model can be solved on its own or iteratively with an AdH model to fully account for the changing hydrodynamics due to wave runup. When solved iteratively, a STWAVE snapshot is periodically produced using the AdH result as the initial condition. Similar to the AdH toolbox, the STWAVE toolbox provides the user with an object-oriented Pythonic wrapper that interacts with the STWAVE engine. All STWAVE functionalities are accessed through calls to a central, controlling model object.

Toolbox: Domain. The ROAMS domain toolbox acquires external data, reformats data to a consistent structure, and stores data for use in the other toolboxes. The domain toolbox is able to utilize most common data types within environmental and hydrodynamic modeling such as discharges, water levels, bathymetry, and wind. It is able to import data from local files as well as use API links to download data from remote sources such as the US Geological Survey (USGS), the National Oceanic and Atmospheric Administration (NOAA), and the National Weather Service (NWS).

The objects within the domain toolbox use a shared inheritance structure based on the data structure, type, and source characteristics to provide a common data interface. The structure of the data refers to whether the data are a single point or a collection of points, and if the data vary temporally. Data type indicates what kind of data are being stored and the functionality that should be provided to the user. Data source intuitively refers to the primary information collector; those sources that do not match the standard data format imposed by the data type are automatically converted before being stored. All data within the same ROAMS instance are stored in Universal Transverse Mercator (UTM) projection and metric units to ensure consistency.

Toolbox: Routing. The ROAMS routing toolbox determines the best waterborne path between two points specified by the user. In the military logistic context, the starting point is often an offshore intermediate staging base with the second point being an onshore location. In the military operations context, the starting point may be a larger vessel with the second point being a target location. The routing toolbox utilizes three stages—preconditioning, optimization, and post-conditioning—to determine a path through the environment between the specified starting and ending locations.

The decision process for vessel routing is, in general, a highly complicated practice that requires knowledge of the route decision metrics as well as the vessel/environmental data necessary to

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[1]*Steady State Spectral Wave*. U.S. Army Engineer Research and Development Center, Coastal and Hydraulics Laboratory, Vicksburg, MS.

evaluate those metrics. To simplify the routing procedure, decision metrics can be divided into first-order and second-order metrics. First-order decision metrics are active variables that must be satisfied for a vessel to operate in a given environment. Second-order metrics are those that are incorporated only once all first-order metrics have been fulfilled. Typical first-order metrics include such variables as draft, vessel maneuverability, and proximity to a region of avoidance. Second-order metrics include a variety of items such as channel centering, route length, full 3D vessel motion, and traffic management. Selecting metrics is important not only to the development of routing algorithms but also to the creation of the necessary hydrodynamic models as the fidelity and features captured are directly impacted by the needed information. The primary focus of the routing toolbox is on satisfying first-order metrics; second-order metrics have been included in the platform as necessary to improve the routing procedure or to meet specific mission criteria.

The preconditioning stage determines if any traversable, waterborne path exists between the specified start/stop locations to provide an initial path for the optimization stage. The preconditioning stage is omitted if the user provides an initial route or if the vessel is part of a multi-vessel operation where the preconditioner has previously calculated a path. The preconditioning algorithm utilizes an A* ("A-star") search to determine the shortest path by stepping between mesh nodes (Patel 2017). A reduction step is done to the output of the A* algorithm to obtain the minimal number of nodes required to maintain a wet path without intersection with land. The use of the A* algorithm guarantees that a wet path, if it exists, will be found, and the path between the starting/landing sites will be the shortest that exists on the mesh. However, the algorithm neither guarantees that the found path will satisfy all navigation requirements nor that there is not a longer, more preferred path based on navigation requirements.

The optimization stage enforces the navigation requirements on the estimated path given by the preconditioner. The penalty/barrier method was selected as its global cost function and can be decomposed into a summation of cost functions over each navigation requirement. This allows each cost function to compensate for the changing importance among the navigation constraints as vessel length and beam vary. It also accounts for the spatial dimension of the path by individually determining the suitability of each node on the path. Scaling the cost magnitude associated with each requirement can also modify the relative importance between navigation requirements. Beginning with the nodes contained in the estimated path, the optimization algorithm alternates between forward and backward sweeps. At each node, the algorithm generates trial points surrounding the node with the distance from the node being proportional to the average length of the forward and backward path segments. If the trial points produce a global cost function value that is less than the current node, the trial node is accepted as the new node. The optimization terminates when the lengths of all segments are less than 150% of the ship length, which is a balance between resolution and computation time.

Penalty Function: Draft. The draft constraint ensures that the vessel operates only in sufficiently deep water to prevent running aground. Freedom of motion is maximized by allowing the algorithm to step through shallower depths to move between wet regions. The draft penalty function is defined as follows:

$$P_d = 0 \qquad h_{forward}, h_{backward} > dS_f$$

$$P_d = C_{draft}\left(dS_f - h_{avg}\right)^2 \qquad h_{avg} = \frac{h_{forward} + h_{backward}}{2} \qquad dS_f \geq h_{forward}, h_{backward} > 0$$

$$P_d = C_{barrier} \qquad h_{forward}, h_{backward} \leq 0$$

where P_d is the draft penalty value, d is the vessel draft, S_f is a safety factor applied to the draft, $h_{forward}$ is the minimum water depth on the forward segment, $h_{backward}$ is the minimum water depth on the backward segment, C_{draft} is the draft coefficient, and $C_{barrier}$ is the minimum value at which the barrier activates. The draft coefficient is chosen such that the function takes a maximum value when the water depth is zero:

$$C_{draft} = \frac{C_{draft}^{max}}{d^2 S_f^2}$$

A discontinuity in the function value exists at zero as the function transitions from parabolic behavior to the barrier value. An appropriate value for C_{draft}^{max} was determined to be 2^{15} when using $C_{barrier} = 10^6$ through a penalty factor sensitivity analysis.

Penalty Function: Maneuverability. Vessel maneuverability is complex and difficult to capture due to the large number of contributing factors. The routing analysis uses a simplified metric given in terms of the maximum turning angle of the vessel. The angle is approximated as the vessel is able to turn one beam width over its length. The maneuverability constraint ensures the angle between route segments remains sufficiently small such that a vessel could physically traverse the calculated path. This is normalized by the corresponding vessel length to give consistent comparison that can be applied to path segments of different lengths:

$$\theta_{norm}^{max} = \frac{arctan\left(\frac{b}{l}\right)}{l}$$

where θ_{norm}^{max} is the maximum turning angle per unit vessel length, b is the vessel beam, and l is the vessel length.

The path trial nodes are evaluated in terms of the angle that is created between the backward, center, and forward segments as the current node is perturbed. The angle penalty function is defined as

$$P_m = C_{maneuver}\left[\frac{\left(\theta_f/d_f\right)^2 + (\theta_c/d_c)^2 + (\theta_b/d_b)^2}{\theta_{norm}^{max\ 2}}\right]$$

where P_m is the maneuverability penalty value, $C_{maneuver}$ is the maneuverability coefficient, θ is the angle between the segments, and d is the segment length. Variables f, c, and b correspond to the forward, center, and backward positions, respectively. Nodes at the start or end of the route neglect the backward or forward angle, as appropriate, and are scaled by a factor of 3/2 to maintain the same order of magnitude as the central nodes. The maneuverability coefficient was chosen such that values were comparable to both the draft and segment length penalties. A reasonable value for the coefficient was found to be on the order of 10^5 through a penalty factor sensitivity analysis.

Penalty Function: Shore Proximity. The shore proximity constraint ensures that the path remains approximately centered in the river cross section. The penalty does not assume a thalweg location, as this is considered in the draft penalty, but rather recognizes that proximity to shore presents an inherent risk that should be minimized. A significant penalty is applied only when the perpendicular distance between the path and shore becomes small compared to the ship length to permit freedom of motion. The shore proximity penalty function is defined as

$$P_s = C_{barrier} \qquad d_s \le b/2$$

$$P_s = C_s(4l - d_s) \qquad b/2 < d_s \le 4l$$

$$P_s = 0 \qquad d_s > 4l$$

where P_s is the shore proximity penalty, C_s is the shore proximity coefficient, and d_s is the perpendicular distance to shore from the segment. The value is calculated for both the forward and backward segments and is therefore total of the two values. The shore proximity coefficient was required to be at least 2^{16} to provide the desired behavior when compared to other penalties function values.

Penalty Function: Segment Length. The segment length penalty is introduced to provide numerical stability and prevent path segments from becoming entangled. At large segment lengths, the segment length penalty must compensate for the tendency of large node movements producing intersections among path segments. At less than 50 m, the initial segment length penalty begins to become detrimental by artificially repelling nodes and producing an unphysical, saw-tooth pattern within the path. The segment length penalty is therefore modified for segments less than 50 m in length to penalize the deviation of trial nodes from the path centerline connecting the forward and backward nodes. When the average of the forward and backward segment lengths are greater than 50 m, the following form of the segment length penalty applies:

$$P_l = C_{barrier} \qquad d_b \le l/2$$

$$P_l = \frac{2C_{barrier}}{l}(l - d_b) \qquad l/2 < d_b \le l$$

$$P_l = d_b - l \qquad d_b > l$$

where P_l is the shore penalty function value. A similar value is calculated for the forward function; the total segment length penalty value is the sum of the forward and backward components. When the average segment length is less than or equal to 50 m, the secondary form of the segment length penalty is applied:

$$P_l = C_{barrier} \qquad d_f \le l/2$$

$$P_l = C_{barrier} \qquad d_f > d_{avg}\sqrt{2}$$

$$P_l = \frac{2C_{barrier}\left|d_{avg} - d_f\right|}{d_{avg}} \qquad l/2 < d_f \le d_{avg}\sqrt{2}$$

where:

$$d_{avg} = \frac{d_f + d_b}{2}$$

A third post-conditioning stage is applied to determine the viability of the path once an optimal route has been calculated. Based on these percentages, a qualitative judgment of the viability of the path is made. The percentages, the viability, and the final route are returned for subsequent use.

Regions of avoidance are handled within the routing algorithm through user-defined polygons that indicate the regions to be excluded. All water depths in the avoidance regions are set to zero, which prevents motion through the region. New nodes are introduced into the AdH/bathymetry mesh to cleanly resolve the region of avoidance polygon without error. The shore proximity penalty function ensures a minimum setback from any specified region of avoidance.

CASE STUDY: The ROAMS platform was applied to a large, northeast American metropolitan region to demonstrate the capability of the platform. The particular urban area was selected due to USACE ongoing interest in the region as well as the existence of a preliminary AdH model for the region from which results could be drawn. As the hydrodynamics of the region are not the central focus of the present work, the details of the AdH model construction will be neglected in favor of a discussion of the routing component. All routes were calculated for the same time-step of the AdH model though ROAMS does include the capability to conduct transient routing analyses as water depth changes.

In the present example, an offshore intermediate staging base has been selected near the mouth of the river approximately central between adjacent jurisdictions. Figure 1 displays the AdH-computed water depths for the analysis. Three possible landing sites were selected: upstream in the river; the eastern continental side of the Sound within the core of the metropolitan region; and the western continental side of the Sound. All routes were calculated using the Expeditionary Fast Transport (EPF), a large, medium-draft military vessel utilized for troop transport and military logistics. When fully loaded, the minimum draft of the vessel is approximately 4.6 m (15 feet [ft]), but the vessel typically operates at greater depths due to its unique propulsion system. The EPF has a length of 137 m (450 ft) and a beam of 32.3 m (106 ft).

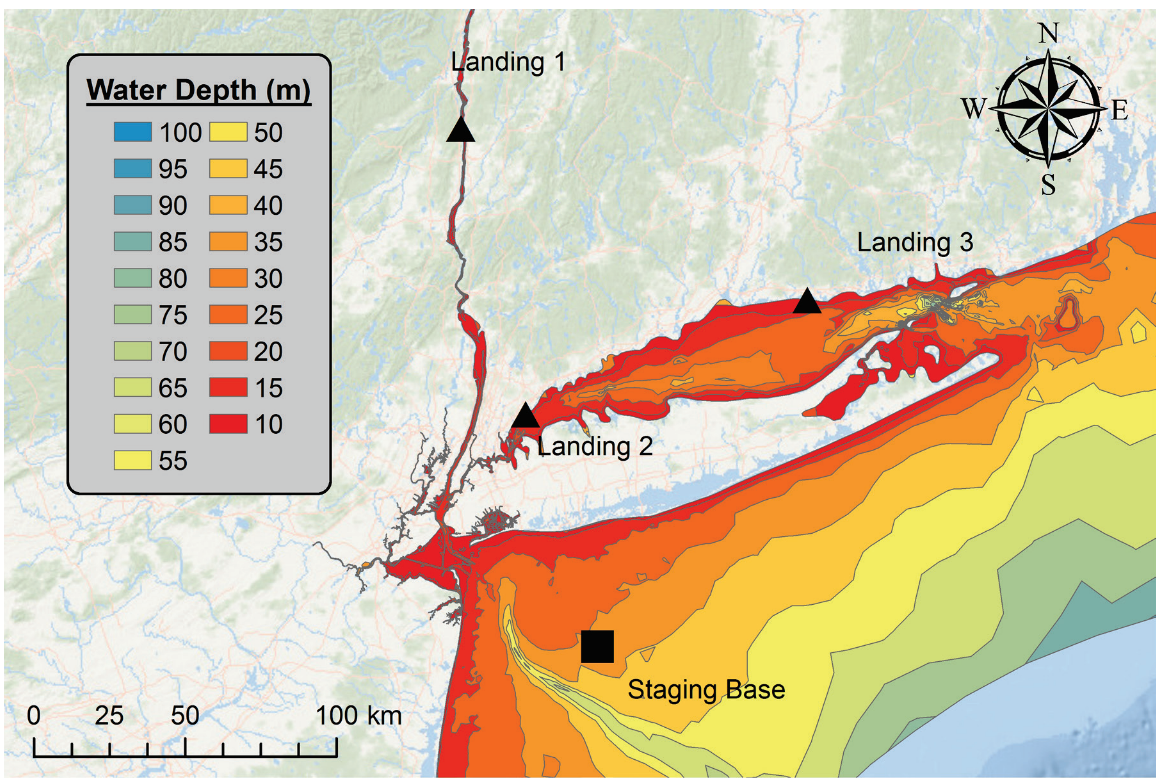
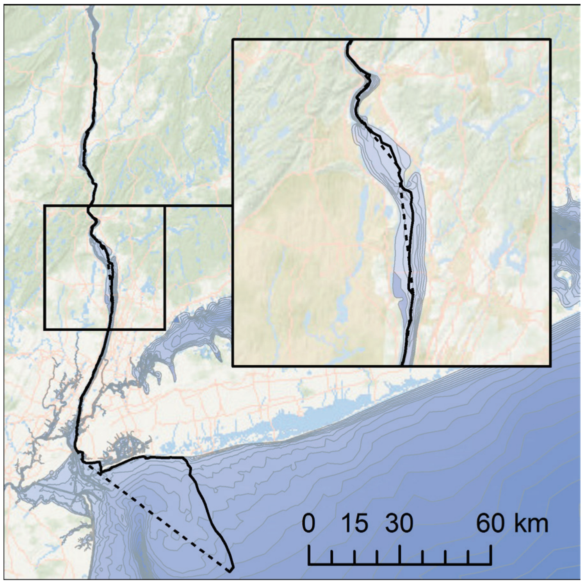


Figure 1. Starting and landing sites utilized in the routing analysis. Water depths, as predicted by AdH, are also shown.

The routing algorithm first applies a preconditioning stage to determine if a wet path exists between the staging base and landing site. Figure 2 illustrates the full and reduced preconditioned paths for Routes 1 and 3, respectively. As mentioned previously, the preconditioner utilizes an A* search algorithm on the mesh and then reduces the number of nodes in the path to the minimum required not crossing land. As evident in the figure, the reduction in the number of nodes in the path typically removes the path from direct contact with the shoreline and results in a path with reduced distance that follows the channel centerline. The typical reduction in the number of path nodes can range from 50% to 90% depending on the domain geometry.



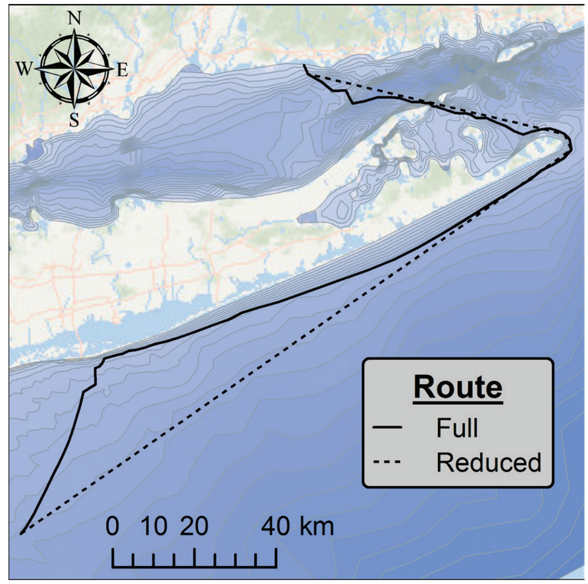


Figure 2. Left – A comparison of the full and reduced paths calculated by the preconditioner for Route 1. The inset expands on a region of the river. Right – A comparison of the full and reduced paths calculation by the preconditioner for Route 3.

Figure 3 shows the final, optimized path for each of three routes. The penalty/barrier technique generally performs well, identifying changes in the domain and modifying the preconditioned path appropriately as witnessed in the river for Route 1. The output of the optimization follows intuition about how to navigate through the environment. Regions within channels are not fully centered over the thalweg and often pass too close to the shoreline. At the entrance to the harbor, the algorithm fails to correctly identify the navigation channel. Instead, it favors a more western approach, likely to minimize the influence of the angle penalty. The west approach satisfies vessel draft; however, pilots are expected to favor the deeper drafts of the navigation channel.

Regions of avoidance can be incorporated to exclude areas of the domain. Figure 4 shows the original Route 1 and the revised Route 1 when an obstruction is introduced at the mouth of the estuary. The preconditioning/optimization stages reroute around the western edge of the island and through an adjacent river. This presents a feasible alternative for medium vessels although the turning angle required to move between the secondary rivers may be problematic for some less-maneuverable vessels. Larger vessels would likely be required to continue in the secondary rivers until they join the main channel due to constrained maneuverability. Presently, the preconditioning stage lacks the capability to dynamically adjust the selected route on criteria other than the vessel draft without the introduction of a region of avoidance.

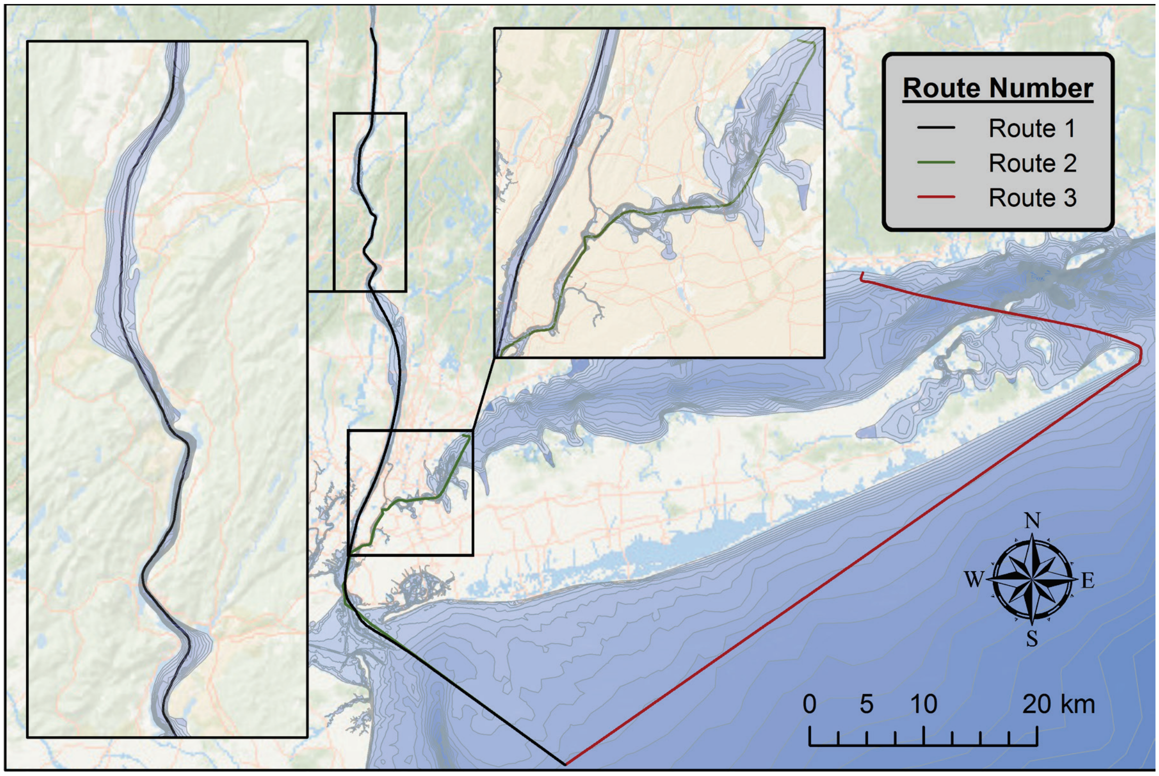


Figure 3. Final vessel paths as calculated by the optimization stage.

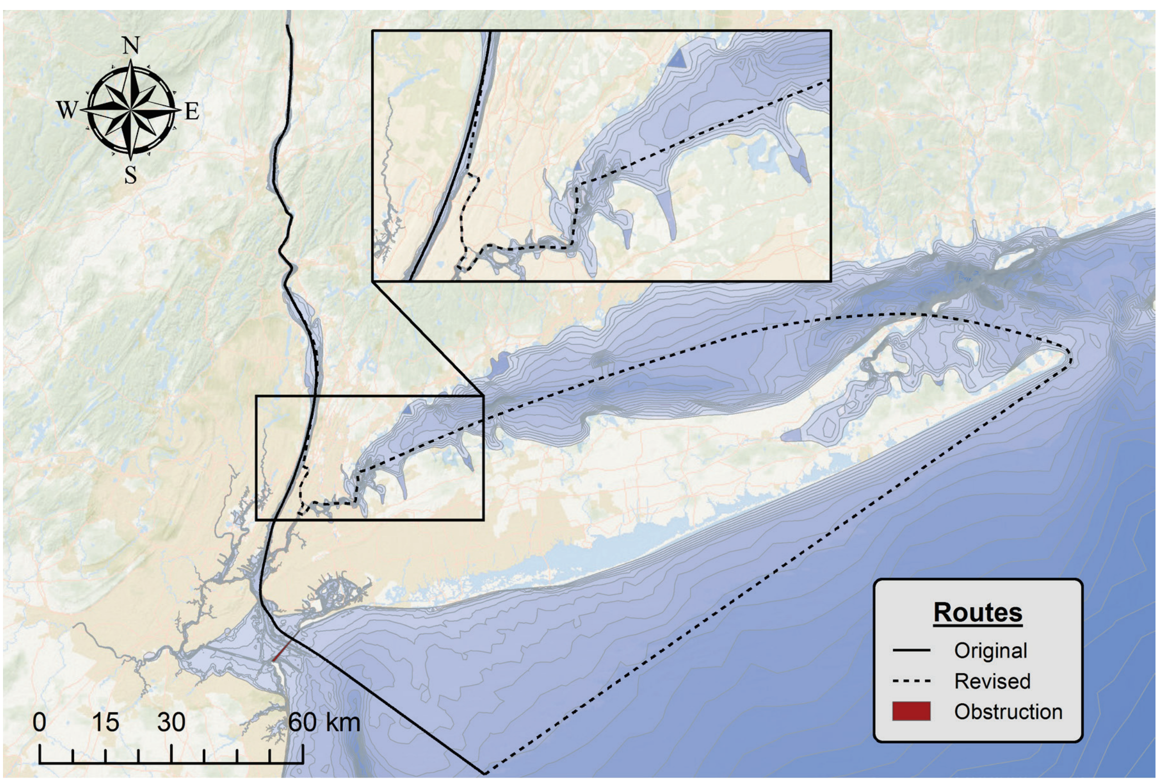


Figure 4. A comparison between the original and revised Route 1 when an obstruction is introduced at the mouth of the estuary.

Post-conditioning is the final routing stage that evaluates the predicted path and provides the user with statistics about its likely navigability. The current version of the post-conditioner provides the user with the percentage of time that both the draft and maneuverability of the criteria are satisfied. Table 1 shows these metrics for analyzed routes.

Table 1. Route evaluation metrics output from the post-conditioning stage.

Route #	Draft Satisfaction (%)	Maneuverability Satisfaction (%)
1	96.49	81.35
2	96.46	70.95
3	99.42	97.75
1 - Revised	99.09	96.34

CONCLUSION: This technical note described the ROAMS v2.0 platform, which supports improved LOC/route characterization by incorporating greater environmental knowledge and an enhanced routing scheme for military logistics and operational activities. The four toolboxes—AdH, STWAVE, domain, and routing—were defined by their roles in the platform. The routing algorithm was described in detail and combined with a case study to demonstrate its effectiveness. Use of the ROAMS v2.0 platform can provide military planners with an increased understanding of environmental conditions, the effect of these conditions on vessel movements, and the subsequent impact of both on military logistics and operational activities.

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